

EVALUATION OF n + 63Cu CROSS SECTIONS FOR THE ENERGY  
RANGE 1.0E-11 to 150 MeV

A. J. Koning, M. B. Chadwick, and P. G. Young  
15 February 1998

This evaluation provides a complete representation of the nuclear data needed for transport, damage, heating, radioactivity, and shielding applications over the incident neutron energy range from 1.0E-11 to 150 MeV. The discussion here is divided into the region below and above 20 MeV.

INCIDENT NEUTRON ENERGIES < 20 MeV

Below 20 MeV the evaluation is based completely on the ENDF/B-VI (Release 2) evaluation by D. Hetrick, C.Y. Fu, and D. Larson.

INCIDENT NEUTRON ENERGIES > 20 MeV

The ENDF/B-VI Release 2 evaluation extends to 20 MeV and includes cross sections and energy-angle data for all significant reactions. The present evaluation utilizes a more compact composite reaction spectrum representation above 20 MeV in order to reduce the length of the file. No essential data for applications is lost with this representation.

The evaluation above 20 MeV utilizes MF=6, MT=5 to represent all reaction data. Production cross sections and emission spectra are given for neutrons, protons, deuterons, tritons, alpha particles, gamma rays, and all residual nuclides produced ( $A>5$ ) in the reaction chains. To summarize, the ENDF sections with non-zero data above  $En = 20$  MeV are:

MF=3 MT= 1 Total Cross Section  
MT= 2 Elastic Scattering Cross Section  
MT= 3 Nonelastic Cross Section  
MT= 5 Sum of Binary (n,n') and (n,x) Reactions

MF=4 MT= 2 Elastic Angular Distributions

MF=6 MT= 5 Production Cross Sections and Energy-Angle Distributions for Emission Neutrons, Protons, Deuterons, Tritons, and Alphas; and Angle-Integrated Spectra for Gamma Rays and Residual Nuclei That Are Stable Against Particle Emission

The evaluation is based on nuclear model calculations that have been benchmarked to experimental data, especially for n + Cu65 and p + Cu65 reactions (Ch98). We use the GNASH code system (Yo92), which utilizes Hauser-Feshbach statistical, preequilibrium and direct-reaction theories. Spherical optical model calculations are used to obtain particle transmission coefficients for the Hauser-Feshbach calculations, as well as for the elastic neutron angular distributions.

Cross sections and spectra for producing individual residual nuclei are included for reactions. The energy-angle-correlations for all outgoing particles are based on Kalbach systematics (Ka88).

A model was developed to calculate the energy distributions of all recoil nuclei in the GNASH calculations (Ch96a). The recoil energy distributions are represented in the laboratory system in

MT=5, MF=6, and are given as isotropic in the lab system. All other data in MT=5, MF=6 are given in the center-of-mass system. This method of representation utilizes the LCT=3 option approved at the November, 1996, CSEWG meeting.

Preequilibrium corrections were performed in the course of the GNASH calculations using the exciton model of Kalbach (Ka77, Ka85), validated by comparison with calculations using Feshbach, Kerman, Koonin (FKK) theory [Ch93]. Discrete level data from nuclear data sheets were matched to continuum level densities using the formulation of Ignatyuk et al. (Ig75) and pairing and shell parameters from the Cook (Co67) analysis. Neutron and charged-particle transmission coefficients were obtained from the optical potentials, as discussed below. Gamma-ray transmission coefficients were calculated using the Kopecky-Uhl model (Ko90).

#### SPECIFIC INFORMATION CONCERNING THE Cu-63 EVALUATION

This evaluation is documented in some detail in Ref. (Ko98b).

The neutron total cross section above 20 MeV was obtained by evaluating experimental data, with a particular emphasis on the Finlay (Fi93) elemental data. This resulted in an evaluated elemental Cu total cross section; to obtain an isotopic  $^{63}\text{Cu}$  total cross section, it was assumed that  $^{63}\text{Cu}$  and  $^{65}\text{Cu}$  have total cross sections in an  $A^{**2/3}$  ratio to one another. The total neutron nonelastic cross section was obtained directly from an optical model calculation (see below), after verifying that it was in good agreement with the experimental data (Ko98b).

To obtain the neutron optical potential we used total cross section data from 1.2 to 4.5 MeV (Gu86) and from 5.3 to 600 MeV (Fi93), and elastic scattering angular distribution data from 1.6 to 96 MeV (Br50, Sa60, Ki74, El82, Gu86). The optical potential parameters were obtained using a combination of a grid search code and the interactive optical model viewer ECISVIEW [Ko97], both built around the coupled channels code ECIS96 [Ra94]. The energy dependence of the optical model parameters is as described in [Ko98]. This optical potential was used for the calculation, with ECIS96, of neutron transmission coefficients and DWBA cross sections for the entire energy region above 20 MeV.

Due to the lack of proton elastic scattering data in numerical form, we used a combination of global optical models for the proton channel. The Becchetti-Greenlees potential [Be69] was adopted below 47 MeV, and the non-relativistic version of the Madland potential [Ma88] above 47 MeV. At this particular energy point the two potentials join smoothly.

For deuterons, the Lohr-Haeberli global potential [Lo74] was used; for alpha particles the Moyen potential (MacFadden-Satchler [Ma66]) was used; and for tritons the Becchetti-Greenlees potential [Be71] was used. The He-3 channel was ignored, due to its small importance.

Following Delaroche et al. [De82], we adopted the weak-coupling model for direct collective inelastic scattering for Cu-63, using Ni-64 as a basis. For the calculation of the cross sections, ECIS96 was used in DWBA mode. We used the following direct transitions for Cu-63 (ground state  $3/2^-$ ) :

Jpi Ex(MeV) Deformation lengths

0.5-	0.669	Delta(2)=0.319
2.5-	0.962	Delta(2)=0.552
3.5-	1.327	Delta(2)=0.638
1.5-	1.547	Delta(2)=0.451
1.5-	3.382	Delta(3)=0.313
2.5-	3.632	Delta(3)=0.384
3.5-	3.882	Delta(3)=0.444
4.5-	4.132	Delta(3)=0.496

No measurements exist for neutron-induced emission spectra above 20 MeV for  $^{63}\text{Cu}$ . However, for  $\text{Cu-65}$  there exists 25.7 MeV ( $n, xn$ ) data by Marcinkowski et al (Ma83). This has been used to benchmark the  $\text{Cu-65}$  data. Without adjusting any of the level density or pre-equilibrium parameters the GNASH calculation was in good agreement with these data. Hence we also adopted these parameters for the whole energy region for  $\text{Cu-63}$ .

\*\*\*\*\*

REFERENCES

- [Ab93] W. Abfalterer, R.W. Finlay, S.M. Grimes, and V. Mishra, Phys. Rev. C47, 1033 (1993).
- [Al83] R. Alarcon and J. Rapaport, Nucl. Phys. A458, 502 (1986).
- [Ar80]. E.D. Arthur and P.G. Young, 'Evaluation of Neutron Cross Sections to 40 MeV for  $^{54,56}\text{Fe}$ ', Proc. Sym. on Neutron Cross Sections from 10 to 50 MeV, 12-14 May 1980, Brookhaven National Laboratory [Eds. M. R. Bhat and S. Pearlstein, BNL-NCS- 51245, 1980] p. 731.
- [Be69]. F.D. Becchetti, Jr., and G.W. Greenlees, Phys. Rev. 182, 1190 (1969).
- [Be71]. F.D. Becchetti, Jr., and G.W. Greenlees in "Polarization Phenomena in Nuclear Reactions," (Ed: H.H. Barschall and W. Haeberli, The University of Wisconsin Press, 1971) p.682.
- [Be92]. O. Bersillon, "SCAT2 - A Spherical Optical Model Code," in Proc. ICTP Workshop on Computation and Analysis of Nuclear Data Relevant to Nuclear Energy and Safety, 10 February-13 March, 1992, Trieste, Italy, to be published in World Scientific Press, and Progress Report of the Nuclear Physics Division, Bruyeres-le-Chatel 1977, CEA-N-2037, p.111 (1978).
- [Br50] Bratenahl, S. Fernbach, R.H. Hildebrand, C.E. Leith, B.J. Moyer, Phys. Rev. 77, 597 (1950)
- [Ch93] M. B. Chadwick and P. G. Young, "Feshbach-Kerman-Koonin Analysis of  $^{93}\text{Nb}$  Reactions:  $P \rightarrow Q$  Transitions and Reduced Importance of Multistep Compound Emission," Phys. Rev. C 47, 2255 (1993).
- [Ch96]. M. B. Chadwick, P. G. Young, R. E. MacFarlane, and A. J. Koning, "High-Energy Nuclear Data Libraries for Accelerator-Driven Technologies: Calculational Method for Heavy Recoils," Proc. of 2nd Int. Conf. on Accelerator Driven Transmutation Technology and

Applications, Kalmar, Sweden, 3-7 June 1996.

[Ch98]. M. B. Chadwick and P. G. Young, "GNASH Calculations of n,p + Cu isotopes and Benchmarking of Results" in APT PROGRESS REPORT: 1 February - 1 March 1998, internal Los Alamos National Laboratory memo, 6 Mar. 1998 from R.E. MacFarlane to L. Waters.

[Co67]. J. L. Cook, H. Ferguson, and A. R. Musgrove, "Nuclear Level Densities in Intermediate and Heavy Nuclei," Aust.J.Phys. 20, 477 (1967).

[De82] J.P. Delaroche, S.M. El-Kadi, P.P. Guss, C.E. Floyd and R.L. Walter, Nucl. Phys. A390, 541 (1982).

[El82] S.M. El-Kadi, C.E. Nelson, F.O. Purser, R.L. Walter, A. Beyerle, C.R. Gould, L.W. Seagondollar, Nucl. Phys. A390, 509 (1982)

[Fi93]. R. W. Finlay, W. P. Abfalterer, G. Fink, E. Monteil, T. Adami, P. W. Lisowski, G. L. Morgan, and R. C. Haight, Phys. Rev. C 47, 237 (1993).

[Gu86] P. Guenther, D.L. Smith, A.B. Smith, J.F. Whalen, Nucl. Phys. A448, 280 (1986)

[Ig75]. A. V. Ignatyuk, G. N. Smirenkin, and A. S. Tishin, "Phenomenological Description of the Energy Dependence of the Level Density Parameter," Sov. J. Nucl. Phys. 21, 255 (1975).

[Ka77]. C. Kalbach, "The Griffin Model, Complex Particles and Direct Nuclear Reactions," Z.Phys.A 283, 401 (1977).

[Ka85]. C. Kalbach, "PRECO-D2: Program for Calculating Freeequilibrium and Direct Reaction Double Differential Cross Sections," Los Alamos National Laboratory report LA-10248-MS (1985).

[Ka88]. C. Kalbach, "Systematics of Continuum Angular Distributions: Extensions to Higher Energies," Phys.Rev.C 37, 2350 (1988); see also C. Kalbach and F. M. Mann, "Phenomenology of Continuum Angular Distributions. I. Systematics and Parameterization," Phys.Rev.C 23, 112 (1981).

[Ki74] W.E. Kinney, F.G. Perey, ORNL-4908 (1974)

[Ko90]. J. Kopecky and M. Uhl, "Test of Gamma-Ray Strength Functions in Nuclear Reaction Model Calculations," Phys.Rev.C 42, 1941 (1990).

[Ko97] A.J. Koning, J.J. van Wijk and J.-P. Delaroche, "ECISVIEW: A Graphical Interface for ECIS95", Proceedings of the NEA Specialists' Meeting on the Nucleon-Nucleus Optical Model up to 200 MeV, Bruyeres-le-Chatel, November 13-15 1996. Available at <http://db.nea.fr/html/science/om200/>.

[Ko98] A.J. Koning, J.-P. Delaroche and O. Bersillon, "Nuclear Data for Accelerator-Driven Systems: Nuclear models, Experiments and Data Libraries", to appear in Nucl. Instr. Meth. A (1998).

[Ko98b] A.J. Koning, M.B. Chadwick, and P.G. Young, "ENDF/B-VI

neutron and proton datafiles up to 150 Mev for  $^{63}\text{Cu}$  and  $^{65}\text{Cu}$ ", Los Alamos National Laboratory report LAUR- (1998); ECN lab and JEFF report (1998).

- [Lo74] J.M. Lohr and W. Haeberli, Nucl. Phys. A232, 381 (1974)
- [Ma66] Macfadden and Satchler, Nuc. Phys. 84, 177 (1966)
- [Ma83] A. Marcinkowski, R.W. Finlay, G. Randers-Pehrson, C.E. Brient, R. Kurup, S. Mellema, A. Meigooni, R. Tailor, Nucl. Phys. A402, 220 (1983).
- [Ma88]. D.G. Madland, "Recent Results in the Development of a Global Medium-Energy Nucleon-Nucleus Optical-Model Potential, " Proc. OECD/NEANDC Specialist's Mtg. on Preequilibrium Nuclear Reactions, Semmering, Austria, 10-12 Feb. 1988, NEANDC-245 'U' (1988).
- [Pe63]. C. M. Perey and F. G. Perey, Phys. Rev. 132, 755 (1963).
- [Ra94] J. Raynal, Notes on ECIS94, CEA Saclay Report CEA-N-2772 (1994)
- [Sa60] G.L. Salmon, Nucl. Phys. 21, 15 (1960)
- [Yo92]. P. G. Young, E. D. Arthur, and M. B. Chadwick, "Comprehensive Nuclear Model Calculations: Introduction to the Theory and Use of the GNASH Code," LA-12343-MS (1992).

29063 = TARGET 1000Z+A (if A=0 then elemental)

1 = PROJECTILE 1000Z+A

Nonelastic, elastic, and Production cross sections for A&lt;5 projectiles in barns:

Energy	nonelas	elastic	neutron	proton	deuteron	triton	helium3	alpha	gamma
2.000E+01	1.407E+00	1.065E+00	1.910E+00	4.988E-01	4.002E-02	2.586E-03	0.000E+00	6.481E-02	4.414E+00
2.200E+01	1.365E+00	1.059E+00	1.902E+00	5.460E-01	4.450E-02	3.430E-03	0.000E+00	6.696E-02	4.313E+00
2.400E+01	1.330E+00	1.059E+00	1.947E+00	6.094E-01	4.932E-02	4.219E-03	0.000E+00	6.797E-02	4.038E+00
2.600E+01	1.304E+00	1.088E+00	2.044E+00	6.566E-01	5.376E-02	4.943E-03	0.000E+00	6.883E-02	3.764E+00
2.800E+01	1.283E+00	1.127E+00	2.150E+00	6.840E-01	5.733E-02	5.571E-03	0.000E+00	7.199E-02	3.535E+00
3.000E+01	1.262E+00	1.174E+00	2.238E+00	6.949E-01	6.112E-02	6.098E-03	0.000E+00	7.484E-02	3.429E+00
3.500E+01	1.214E+00	1.314E+00	2.331E+00	7.261E-01	6.574E-02	7.022E-03	0.000E+00	7.908E-02	3.412E+00
4.000E+01	1.174E+00	1.438E+00	2.372E+00	7.821E-01	6.955E-02	7.672E-03	0.000E+00	8.154E-02	3.365E+00
4.500E+01	1.138E+00	1.525E+00	2.448E+00	8.292E-01	7.215E-02	8.109E-03	0.000E+00	8.452E-02	3.204E+00
5.000E+01	1.104E+00	1.585E+00	2.529E+00	8.667E-01	7.361E-02	8.438E-03	0.000E+00	8.927E-02	3.036E+00
5.500E+01	1.071E+00	1.613E+00	2.594E+00	9.050E-01	7.402E-02	8.718E-03	0.000E+00	9.358E-02	2.923E+00
6.000E+01	1.040E+00	1.597E+00	2.639E+00	9.450E-01	7.420E-02	9.014E-03	0.000E+00	9.757E-02	2.816E+00
6.500E+01	1.010E+00	1.573E+00	2.675E+00	9.826E-01	7.331E-02	9.305E-03	0.000E+00	1.019E-01	2.704E+00
7.000E+01	9.818E-01	1.539E+00	2.685E+00	1.011E+00	7.481E-02	9.701E-03	0.000E+00	1.065E-01	2.483E+00
7.500E+01	9.557E-01	1.482E+00	2.719E+00	1.045E+00	7.473E-02	1.026E-02	0.000E+00	1.125E-01	2.423E+00
8.000E+01	9.315E-01	1.415E+00	2.752E+00	1.077E+00	7.305E-02	1.094E-02	0.000E+00	1.186E-01	2.346E+00
8.500E+01	9.093E-01	1.344E+00	2.784E+00	1.109E+00	7.358E-02	1.185E-02	0.000E+00	1.252E-01	2.283E+00
9.000E+01	8.890E-01	1.282E+00	2.805E+00	1.133E+00	7.352E-02	1.269E-02	0.000E+00	1.299E-01	2.213E+00
9.500E+01	8.705E-01	1.216E+00	2.818E+00	1.156E+00	7.408E-02	1.360E-02	0.000E+00	1.346E-01	2.178E+00
1.000E+02	8.536E-01	1.143E+00	2.830E+00	1.179E+00	7.473E-02	1.458E-02	0.000E+00	1.390E-01	2.143E+00
1.100E+02	8.243E-01	1.014E+00	2.866E+00	1.228E+00	7.669E-02	1.690E-02	0.000E+00	1.476E-01	2.039E+00
1.200E+02	8.003E-01	8.986E-01	2.900E+00	1.270E+00	7.870E-02	1.939E-02	0.000E+00	1.556E-01	1.957E+00
1.300E+02	7.809E-01	8.038E-01	2.927E+00	1.311E+00	8.110E-02	2.191E-02	0.000E+00	1.618E-01	1.880E+00
1.400E+02	7.654E-01	7.200E-01	2.949E+00	1.346E+00	8.324E-02	2.440E-02	0.000E+00	1.671E-01	1.843E+00
1.500E+02	7.532E-01	6.497E-01	2.978E+00	1.382E+00	8.490E-02	2.704E-02	0.000E+00	1.722E-01	1.796E+00

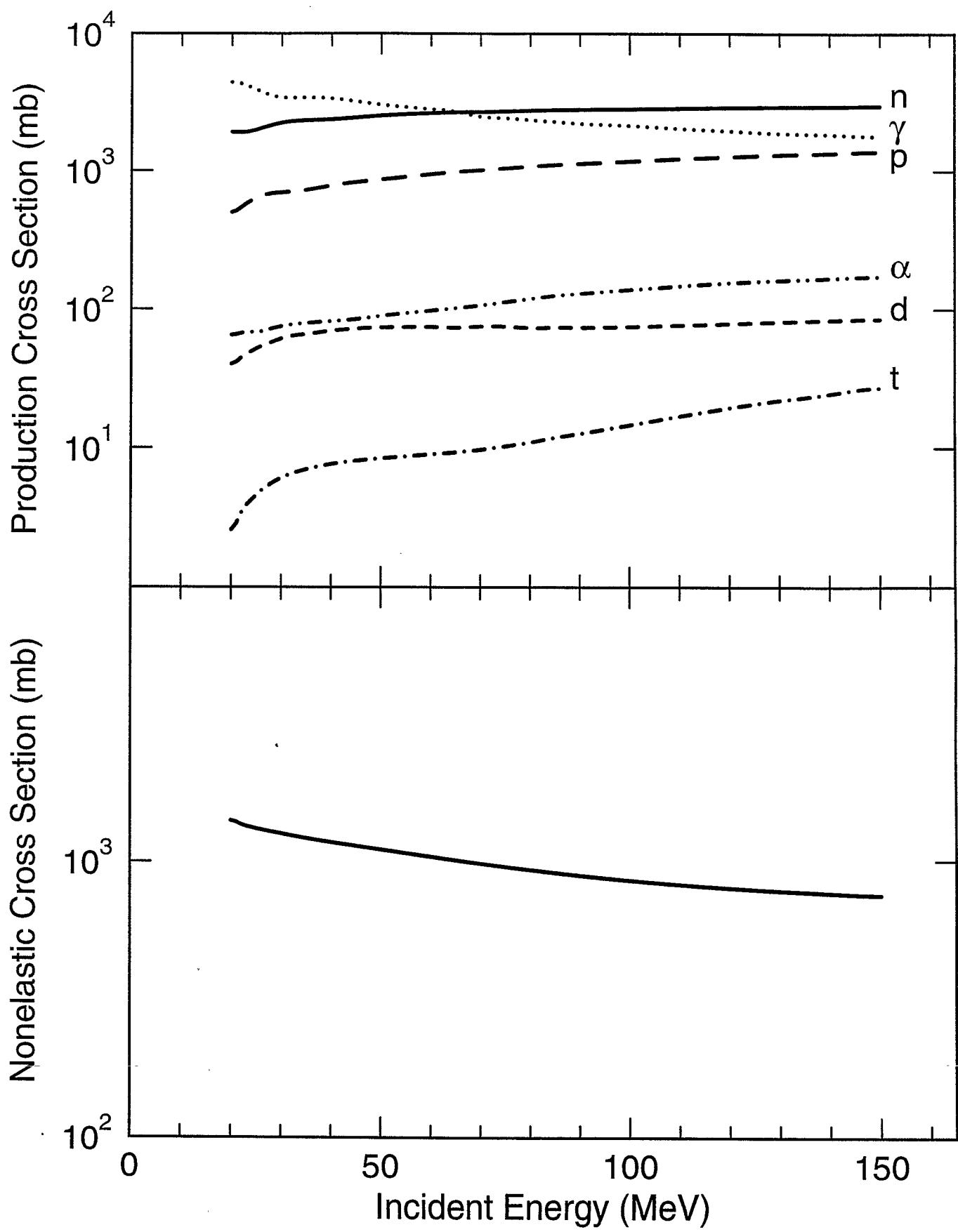
29063 = TARGET 1000Z+A (if A=0 then elemental)

1 = PROJECTILE 1000Z+A

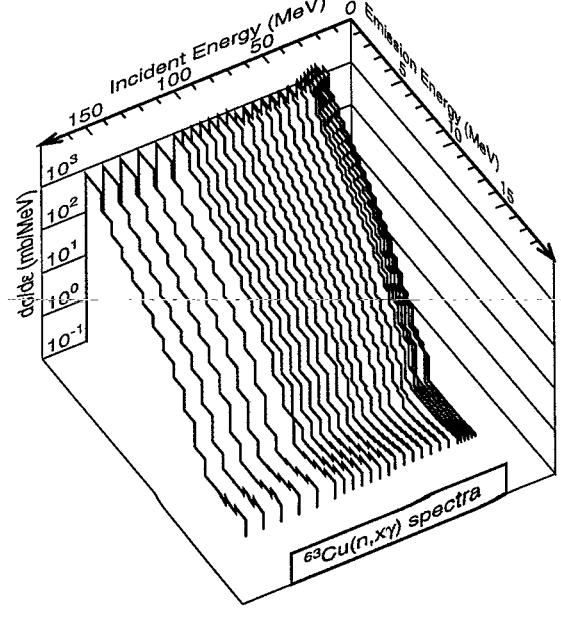
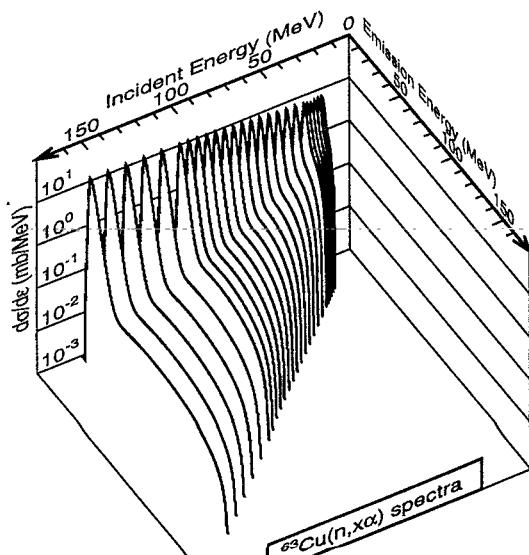
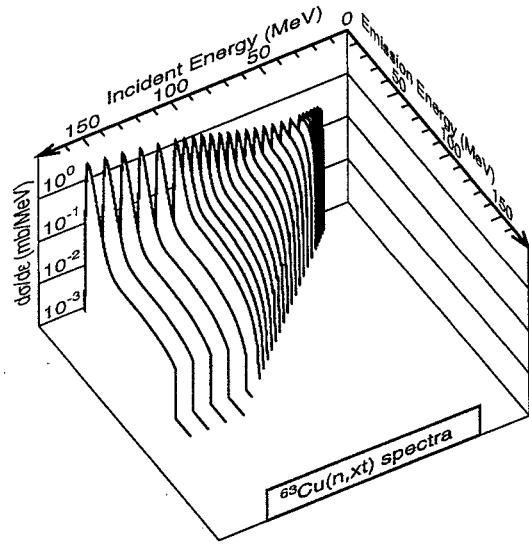
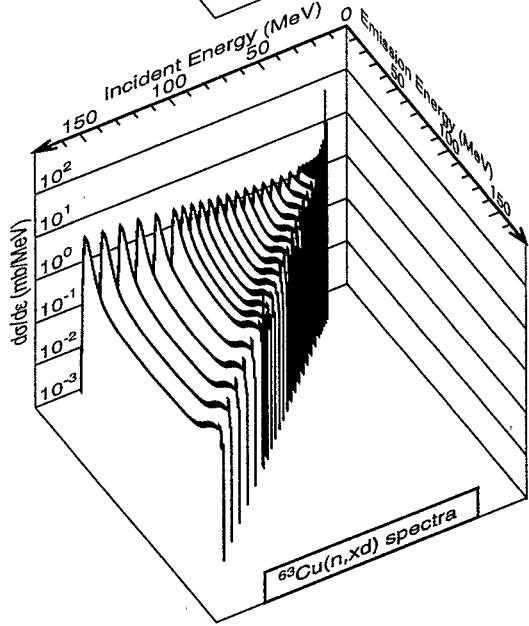
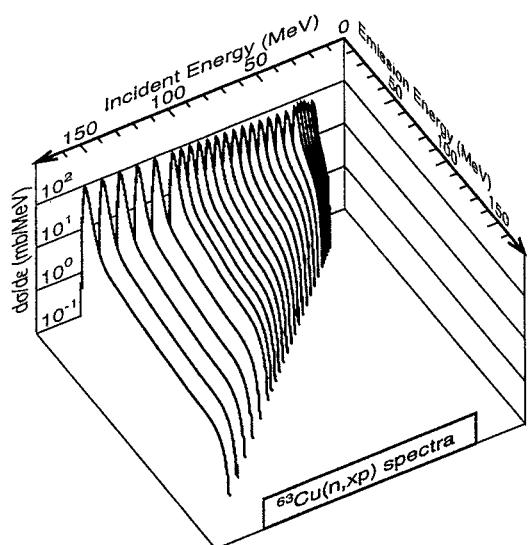
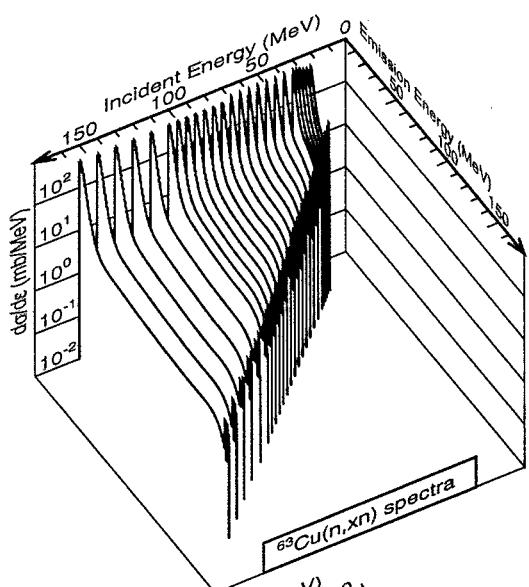
Kerma coefficients in units of f.Gy.m^2:

Energy	proton	deuteron	triton	helium3	alpha	non-rec	elas-rec	TOTAL
2.000E+01	4.860E-01	6.443E-02	2.857E-03	0.000E+00	9.816E-02	8.659E-02	1.914E-02	7.571E-01
2.200E+01	5.510E-01	7.874E-02	4.264E-03	0.000E+00	1.054E-01	9.097E-02	2.127E-02	8.517E-01
2.400E+01	6.307E-01	9.552E-02	5.792E-03	0.000E+00	1.101E-01	9.531E-02	2.259E-02	9.600E-01
2.600E+01	7.112E-01	1.129E-01	7.391E-03	0.000E+00	1.134E-01	9.962E-02	2.360E-02	1.068E+00
2.800E+01	7.890E-01	1.291E-01	8.993E-03	0.000E+00	1.198E-01	1.038E-01	2.403E-02	1.175E+00
3.000E+01	8.585E-01	1.478E-01	1.056E-02	0.000E+00	1.258E-01	1.073E-01	2.408E-02	1.274E+00
3.500E+01	1.046E+00	1.852E-01	1.401E-02	0.000E+00	1.382E-01	1.151E-01	2.367E-02	1.522E+00
4.000E+01	1.252E+00	2.265E-01	1.721E-02	0.000E+00	1.470E-01	1.227E-01	2.272E-02	1.788E+00
4.500E+01	1.453E+00	2.661E-01	1.996E-02	0.000E+00	1.556E-01	1.293E-01	2.150E-02	2.045E+00
5.000E+01	1.644E+00	3.014E-01	2.238E-02	0.000E+00	1.668E-01	1.350E-01	2.035E-02	2.290E+00
5.500E+01	1.825E+00	3.302E-01	2.450E-02	0.000E+00	1.775E-01	1.397E-01	1.921E-02	2.516E+00
6.000E+01	2.002E+00	3.552E-01	2.642E-02	0.000E+00	1.875E-01	1.434E-01	1.789E-02	2.733E+00
6.500E+01	2.179E+00	3.718E-01	2.809E-02	0.000E+00	1.978E-01	1.461E-01	1.675E-02	2.939E+00
7.000E+01	2.342E+00	4.065E-01	2.973E-02	0.000E+00	2.083E-01	1.494E-01	1.570E-02	3.152E+00
7.500E+01	2.504E+00	4.275E-01	3.123E-02	0.000E+00	2.215E-01	1.522E-01	1.458E-02	3.351E+00
8.000E+01	2.667E+00	4.286E-01	3.278E-02	0.000E+00	2.346E-01	1.536E-01	1.351E-02	3.530E+00
8.500E+01	2.822E+00	4.471E-01	3.437E-02	0.000E+00	2.489E-01	1.559E-01	1.250E-02	3.720E+00
9.000E+01	2.979E+00	4.597E-01	3.592E-02	0.000E+00	2.601E-01	1.574E-01	1.165E-02	3.903E+00
9.500E+01	3.133E+00	4.784E-01	3.746E-02	0.000E+00	2.712E-01	1.588E-01	1.084E-02	4.090E+00
1.000E+02	3.292E+00	4.968E-01	3.900E-02	0.000E+00	2.820E-01	1.599E-01	1.003E-02	4.280E+00
1.100E+02	3.605E+00	5.330E-01	4.195E-02	0.000E+00	3.036E-01	1.624E-01	8.652E-03	4.655E+00
1.200E+02	3.922E+00	5.636E-01	4.408E-02	0.000E+00	3.242E-01	1.645E-01	7.518E-03	5.026E+00
1.300E+02	4.246E+00	5.995E-01	4.589E-02	0.000E+00	3.419E-01	1.716E-01	6.628E-03	5.412E+00
1.400E+02	4.579E+00	6.322E-01	4.774E-02	0.000E+00	3.579E-01	1.797E-01	5.877E-03	5.803E+00
1.500E+02	4.931E+00	6.504E-01	5.003E-02	0.000E+00	3.738E-01	1.864E-01	5.264E-03	6.197E+00

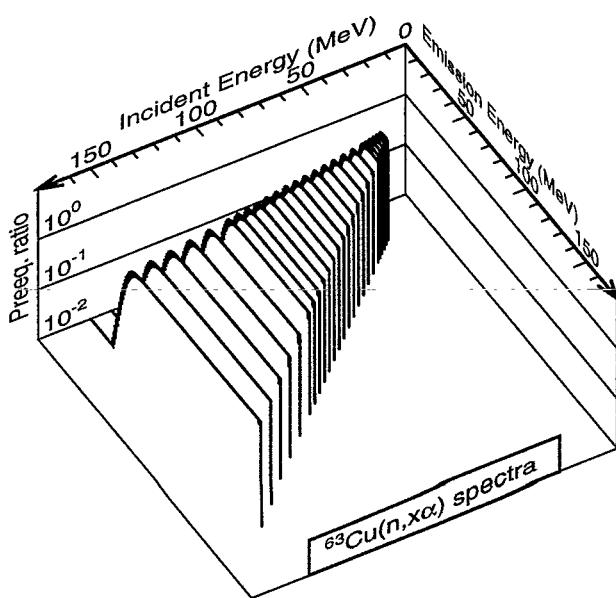
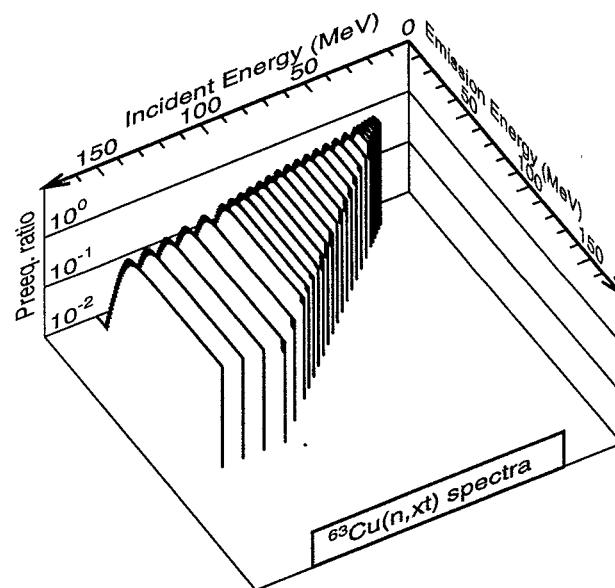
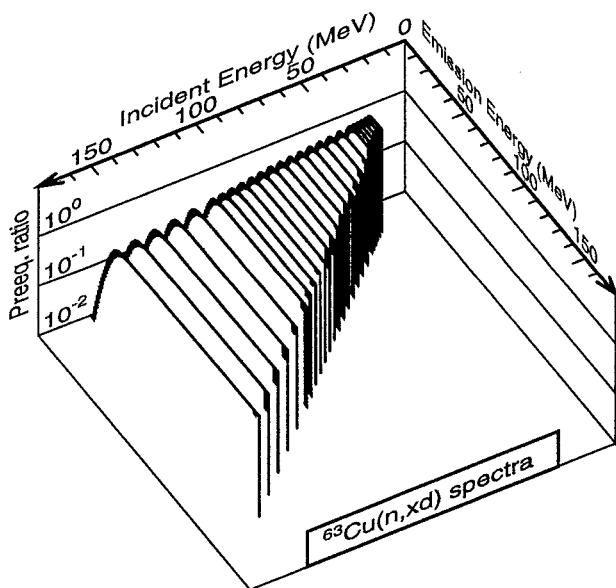
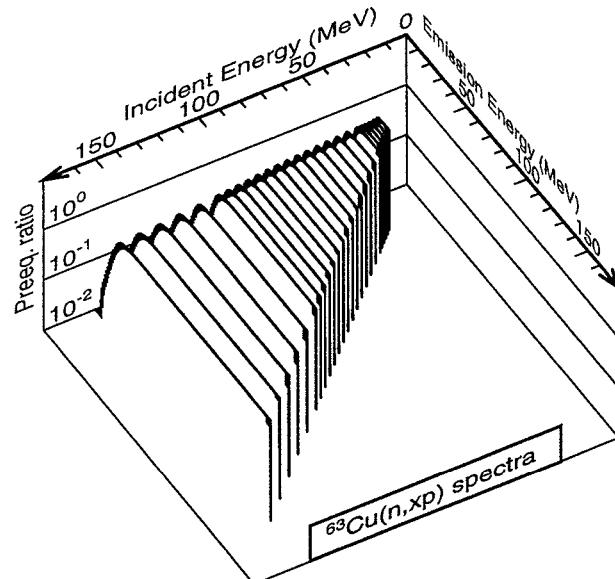
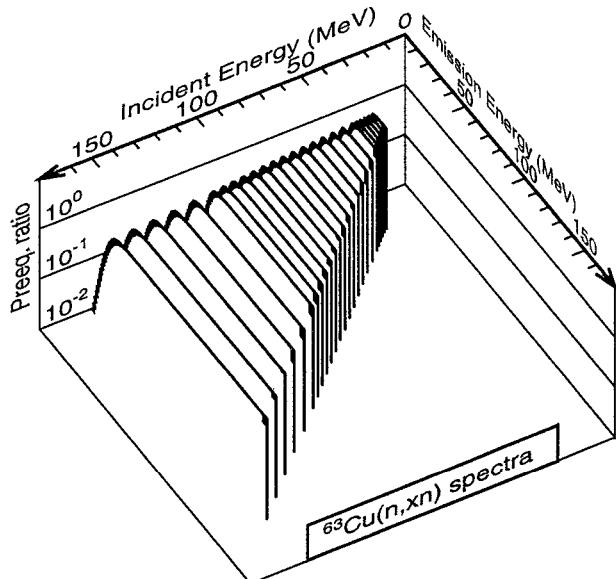
$n + {}^{63}\text{Cu}$  nonelastic and production cross sections



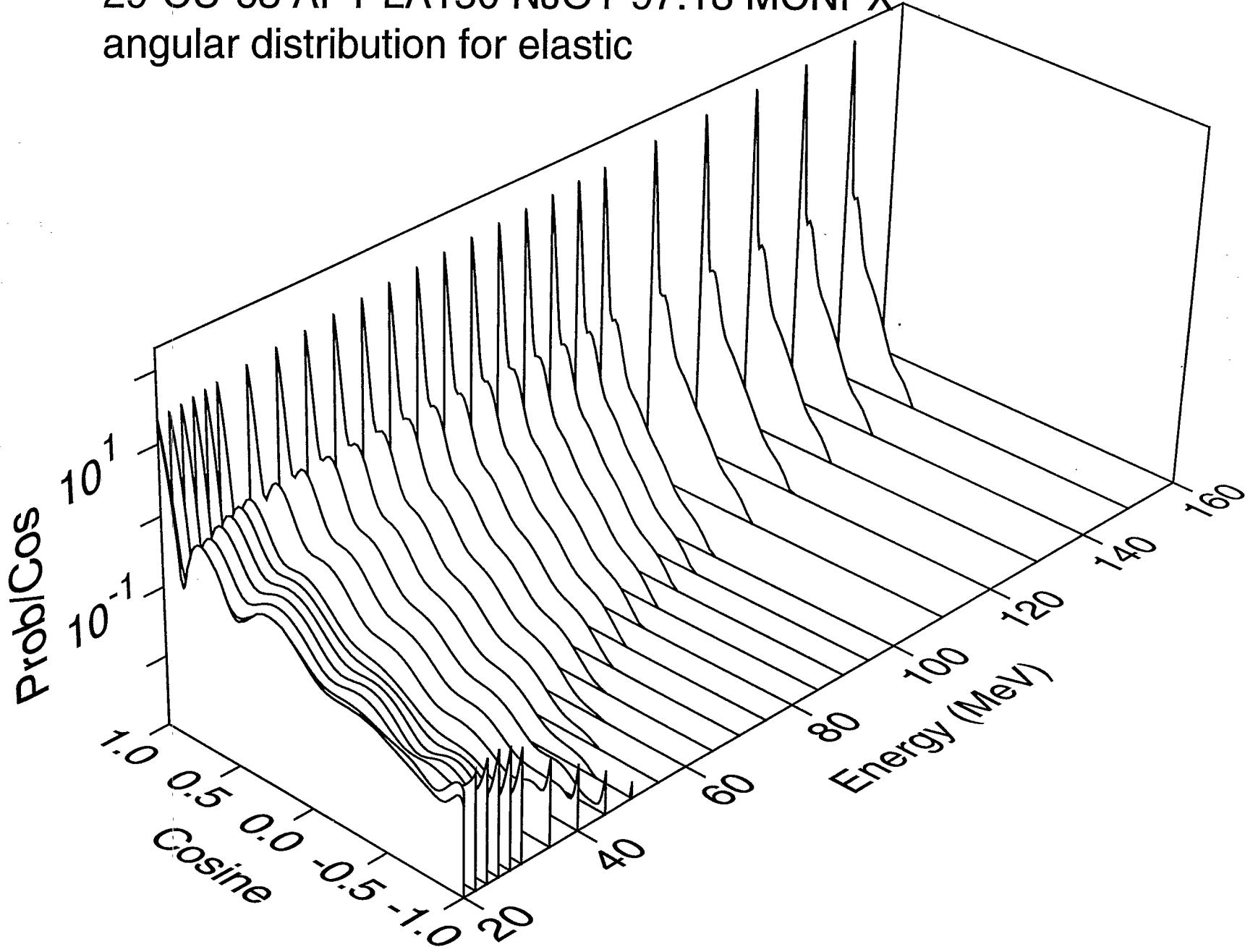
# $n + {}^{63}\text{Cu}$ angle-integrated emission spectra



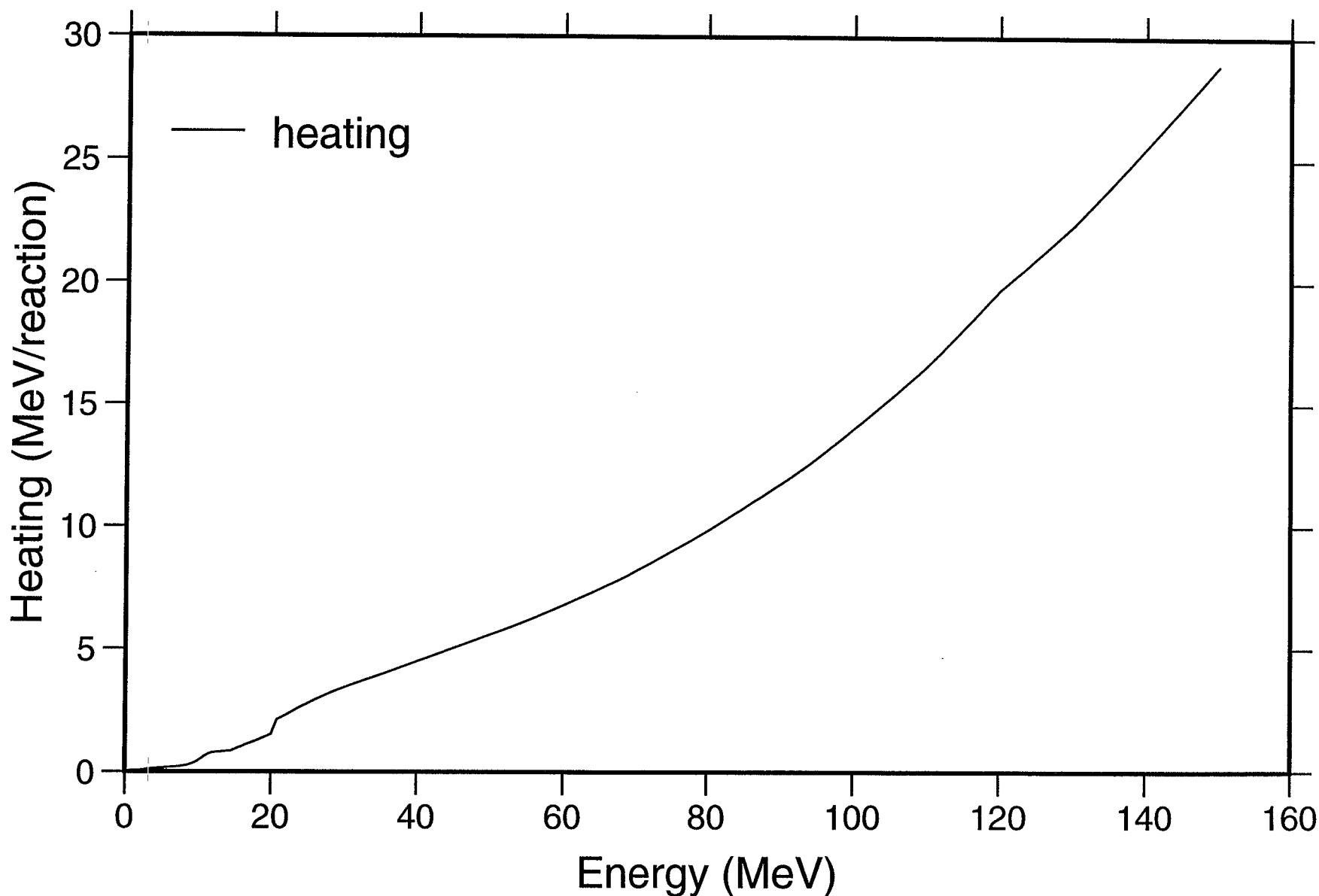
# $n + {}^{63}\text{Cu}$ Kalbach preequilibrium ratios



29-CU-63 APT LA150 NJOY 97.18 MCNPX  
angular distribution for elastic



29-CU-63 APT LA150 NJOY 97.18 MCNPX  
Heating



29-CU-63 APT LA150 NJOY 97.18 MCNPX  
Damage

